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Film Boiling Heat Transfer from a Downward-facing Hemisphere

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Abstract

As an in-vessel retention through external vessel cooling (IVR-EVC) design concept, the external cooling of reactor vessel was suggested to protect the lower head from being overheated due to relocated material from the core during a severe accident. Several issues arose from the design of the APR-1400 (Advanced Power Reactor 1400 MWe) that originally had no consideration for the IVR-EVC. In this study, an experimental facility, DELTA (Downward-boiling Experimental Layout for Transient Analysis), was set up for quenching tests of a scaled-down hemispherical vessel with delayed flooding. Film boiling heat transfer coefficients for a downward facing hemispherical surface were measured by the quenching tests. Material of the test section is copper to maintain the Biot number (Bi) below 0.1. The main conclusion of this study is that the measured film boiling heat transfer coefficients were greater than those predicted by the previous laminar film boiling correlations.

1. Introduction

During the basic design (Phase II) for the APR-1400, the external cooling of the reactor vessel lower head was chosen as the severe accident management strategy, and is in the process of design optimization and licensing during Phase III. The cavity flooding was selected as the external vessel cooling method because of the relatively simpler installation than that of flooding within the thermal insulator. In fact, the IVR-EVC concept had not been initially considered during Phase I (1992-1994): decision of a reactor type and the conceptual design for the reactor vessel lower head. Thus several issues surfaced while applying the IVR concept at a later stage of design. One of these issues was the delayed flooding of the reactor vessel because of the large volume between the cavity floor and the reactor vessel lower head. The cavity flooding and flooding within the thermal insulator may take as large as forty minutes. It is thus not certain that the flooding time is shorter than that of relocation of the molten core down to the lower plenum of the reactor vessel. Analyses on the film boiling for the sphere were performed in reduced scale vessel segments. The film boiling heat transfer coefficients for a sphere were applied to the liquid surrounding a small hot metal particle. Use of the film boiling heat transfer coefficients of the former correlations will be less than the actual value. In case of the vertical plate, Bui and Dhir [1] showed that the measured film boiling heat transfer coefficient was higher than that predicted for the laminar film boiling. No experiments were performed for the downward-facing hemisphere on a large scale, however. Generally, the film boiling heat transfer coefficients were measured by the quenching experiments. In this study, an experimental facility was built for the quenching experiment. Heat transfer coefficients were calculated from the measured temperature.

2. Literature Survey

Bui and Dhir [1] investigated the saturated film boiling on a vertical surface. They noted that both long and short waves exist on the interface between the liquid and vapor film. The long waves evolve into large bulges, and the vapor from the intervening thin-film region feeds the large bulges. As a result the flow path shortens, and higher average heat transfer rates occur than those predicted for a continuous flow path. They also noted that a significant variation in the local heat transfer coefficient exists with time for large bulges and thin-film regions.

Stevens and Witte [2] performed the experiments for transition boiling from 0.75 inch diameter sphere. The copper sphere moving through the subcooled distilled water was experimentally investigated. High-speed photographs showed that transition occurred as a rapidly pulsating vapor film on the forward portion of the sphere. The behavior of the vapor wake is highly dependent upon the manner in which the vapor is being formed on the forward portion of the sphere. Instantaneous heat transfer rates calculated from experimental temperature-time measurements indicate that film and transition boiling are effective as nucleate boiling over the velocity range, 9.6-20.0 fps, in highly subcooled water.

El-Genk and Glebov [3] investigated experimentally the film boiling from a downward facing curved surface in saturated and 5 K, 10 K, and 14 K subcooled water. Local and surface average Nusselt number (Nu) correlations developed for both saturated and subcooled conditions were within 10 % scatter. Surface rewetting was hydrodynamically driven in the saturated boiling, while thermally driven in the subcooled boiling. Consequently, the surface rewetting in the saturated boiling occurred earlier at higher minimum heat flux, and the critical film thickness prior to rewetting was greater than that at 10 K and 14 K subcooled water, but lower than that at 5 K subcooled boiling. Surface rewetting occurred first at the bottom region, then sequentially at higher inclinations. The critical thickness increased with increased inclination and decreased subcooling in the water.

Tou and Tso [4] derived an analytical model for stable film boiling from sphere following the classical approach of Frederking and Clark [5] but using the spherical coordinates. The improvement showed that Nu should approach the value of 2 instead of zero, as the Rayleigh number (Ra) goes to zero. The heat transfer coefficient was larger than that obtained from the classical approach.

Kolev [6] presented a closed analytical solution for the mixed-convection film boiling on vertical walls. Heat transfer coefficients predicted by the proposed model and some experimental data were compared. All data predicted were within the ±10 % error band, with the mean averaged error being less than 4 %. The obtained solution was recommended for practical applications. The new semi-empirical film-boiling model for spheres used in the IVA4 computer code was compared with the experimental data base obtained by Liu and Theofanous. The data were predicted within the ±30 % error band.

3. Experimental Setup and Data Reduction

The hemispherical test section had five K-type thermocouples. To ensure good contact between the thermocouples and the test section wall during installation of the stainless steel disk and the Fire Stop, the epoxy bond was developed at the top of the holes. The holes were drilled through the center of the stainless steel disk, stainless steel pipe and Fire Stop for routing the wall thermocouples to the data acquisition system, HP-VXI E1413C. Material of the test section is copper to maintain Bi below 0.1. The thickness of the copper hemisphere was 3 cm for data from the quenching experiment equal to the data from the steady state experiment by Peyayopanakul and Westwater [7]. If the time to traverse the top 10 % of the boiling curve was greater than 1 sec, the boiling process was quasi-steady state according to Dhir [8]. The test section's inner cavity was filled with bulk fiber thermal insulation and covered on top with Fire Stop disk for additional insulation. A stainless steel disk was fastened to the test section wall using eight stainless steel bolts. Figure 1 shows the cross-sectional view of the test section.

The quenching tank was of 1.00 × 1.00 × 1.10 m. According to Westwater et al. [9], a tank diameter must have 3.5 times the length as that of the test section to maintain the pool boiling condition without the effect of the size of the quenching tank. It had large glass windows on one side, which are used for visual observation and recording of the pool boiling on the hemispherical surface during quenching using the video camera. During the experiment, the water in the tank was maintained at saturated condition using four 10 kW and two 7 kW immersed electric heaters.

Prior to each quenching experiment, the distilled water in the tank was degassed by boiling for thirty minutes. The test section was heated up to 280°C. The heated test section was transferred from the furnace to the quenching tank by the automatic lift for thirty seconds. The heated test section then was submerged in the quenching tank, with its top surface kept 10 cm below the water level. Figure 2 shows the experimental facility, DELTA.

Experiments were set up to measure the film boiling heat transfer coefficient. This experiment was designed for measurement of the temperature profile pursuant to boiling heat transfer. To calculate the overall heat transfer coefficient based on the experimental temperature data, it is necessary to solve the transient heat conduction equation during quenching of the downward facing copper hemisphere. Because of the relative low heat transfer coefficient in film boiling and very high thermal conductivity of the copper, Bi was smaller than 0.1. In case of Bi less than 0.1, the conduction heat transfer in the solid could be neglected as argued in Incropera and Dewitt [10]. The transient heat equation without the conduction term was written as

$$\rho c_p V \frac{\partial T}{\partial t} = h_t A_{out} \left(T - T_{sat} \right) \tag{1}$$

The overall heat flux and film boiling heat transfer coefficient on the outer wall are calculated from the temperature history as follows

$$q'' = \rho c_p \frac{V}{A_{out}} \frac{\partial T}{\partial t} = \frac{\rho c_p V}{A_{out}} \frac{\Delta T}{\Delta t} \tag{2}$$

$$h_t = \frac{\rho c_p V}{A_{out}\left(T - T_{sat}\right)} \frac{\Delta T}{\Delta t} \tag{3}$$

$$h_f = h_t - 0.75 h_{rad} \tag{4}$$

Temperature history was smoothed by means of 10 points FFT-filter in Origin 6.0.

4. Results and Discussion

Figure 3 shows the temperature history from the DELTA experiments. Initially, the temperature of the test section is reduced through film boiling heat transfer. When the wall superheat of the test section reaches 100 K, rewetting of the outer surface occurs.

Figure 4 presents the heat flux with the wall superheat. The minimum heat flux is about 20 kW/m^2. The value is tantamount to El-Genk and Gao [11]'s results. Thus, the wall thermal properties have little effect on the minimum heat flux. The wall superheat at the minimum heat flux is 100 K. According to El-Genk and Gao [11], the wall superheats at the minimum heat flux on the aluminum and stainless steel hemisphere were 125 K and 145 K, respectively. The reason for the wall superheat difference between the aluminum and stainless steel was difference in the wall thermal properties. As the thermal diffusivity of aluminum is similar to that of copper, higher thermal conductivity results in lower wall superheat at the minimum heat flux. However, the maximum heat fluxes in these experiments are 100 kW/m^2 that is lower than the general critical heat flux values. This is because the thermal conduction heat transfer was ignored within the test section. At the maximum heat flux, Bi exceeds 0.1.

Figure 5 illustrates the film boiling heat transfer coefficients with the wall superheat. The measured heat transfer coefficients are larger that those predicted by the laminar film boiling correlation. It shows that the film boiling on the relatively large diameter hemisphere is not laminar. It is therefore necessary to develop a new model accounting for the interfacial wavy motion and the bubble detachment on the interface between the vapor film and the liquid. The difference in the edge angle increased the heat transfer coefficients over those reported by El-Genk and Glebov [3].

Generally, correlations for the film boiling heat transfer coefficient take on the following functional form.

$$Nu = C\left(\frac{Ra}{Ja}\right)^n \tag{5}$$

Table 1 lists the values for the constants C and n in Equation (5).

5. Conclusion and Future Work

In this study, the film boiling heat transfer coefficients on the downward facing hemisphere were obtained from the measured temperatures. The major results may be summarized as follows.

1. The minimum heat flux value in this study is similar to that in El-Genk and Gao.
2. The wall superheat at the minimum heat flux is 100 K. From this study and El-Genk and Gao’s study, the high thermal conductivity lowers the wall superheat at the minimum heat flux.
3. The maximum heat flux in this experiment is a tenth of the generally reported critical heat flux.
4. The film boiling heat transfer coefficients in this study are larger than those predicted by the laminar film boiling correlation.

As follow-up to the present study, the maximum heat flux will be obtained from the measured temperatures and the conduction heat transfer consideration. The effect of the test section diameter on the film boiling heat transfer coefficient will be investigated.

Nomenclature

A_{out}	area of outer surface of test section
c_p	specific heat of test section
h_f	film boiling heat transfer coefficient
h_{rad}	radiation heat transfer coefficient
h_t	total heat transfer coefficient
Ja	Jacob number
Nu	Nusselt number
q''	heat flux on the outer surface
Ra	Rayleigh number
T	temperature of test section
T_{sat}	temperature of water in the saturated condition
t	time
V	volume of test section
ρ	density of test section
Δ	difference

References

1. T.D. Bui and V.K. Dhir, “Film Boiling Heat Transfer on an Isothermal Vertical Surface,” Journal of Heat Transfer, vol. 107, pp. 764-771, 1985
2. J.W. Stevens and L.C. Witte, “Transient Film Boiling and Transition Boiling from a Sphere,” International Journal of Heat and Mass Transfer, vol. 14, pp. 443-450, 1971
3. M.S. El-Genk and A.G. Glebov, “Film Boiling from a Downward Facing Curved Surface in Saturated and Subcooled Water,” International Journal of Heat and Mass Transfer, vol. 39, issue 2, pp. 275-288, 1995
4. S.K.W. Tou and C.P. Tso, “Improvement on the Modeling of Film Boiling on Spheres,”

International Communications in Heat and Mass Transfer, vol. 24, no. 6, pp. 879-888, 1997

5. T.H. Frederking and J.A. Clark, “Natural Convection Film Boiling on a Sphere,” Adv. Cryogen. Eng., vol. 8, pp. 501-506, 1963
6. N.I. Kolev, “Film Boiling on Vertical Plates and Spheres,” Experimental Thermal and Fluid Science, vol. 18, pp. 97-115, 1998
7. W. Peyayopanakul and J.W. Westwater, “Evaluation of the Unsteady-state Quenching Methods for Determining Boiling Curves,” International Journal of Heat and Mass Transfer, vol. 21, pp. 1437-1445, 1978
8. V.K. Dhir, “Boiling Heat Transfer,” Annual Review of Fluid Mechanics, vol. 30, pp. 365-401, 1998
9. J.W. Westwater, J.J. Hwalek and M.E. Irving, “Suggested Standard Method for Obtaining Boiling Curves by Quenching,” Ind. Eng. Chem. Fundam., vol. 25, pp. 685-692, 1986
10. F.P. Incropera, D.P. Dewitt, “Introduction to Heat Transfer,” 3rd Edition, John Wiley & Sons, NewYork, NY, USA, 1996
11. M.S. El-Genk and C. Gao, “Experiments on Pool Boiling of Water from Downward Facing Hemisphere,” Nuclear Technology, vol. 125, pp. 52-69, 1999

Table 1. Constants for Film Boiling Heat Transfer Coefficient in Equation (5)

	This Study	Frederking & Clark [5]	El-Genk & Glebov [3]
C	1.5589	0.723	4.8
n	0.2353	0.25	0.162

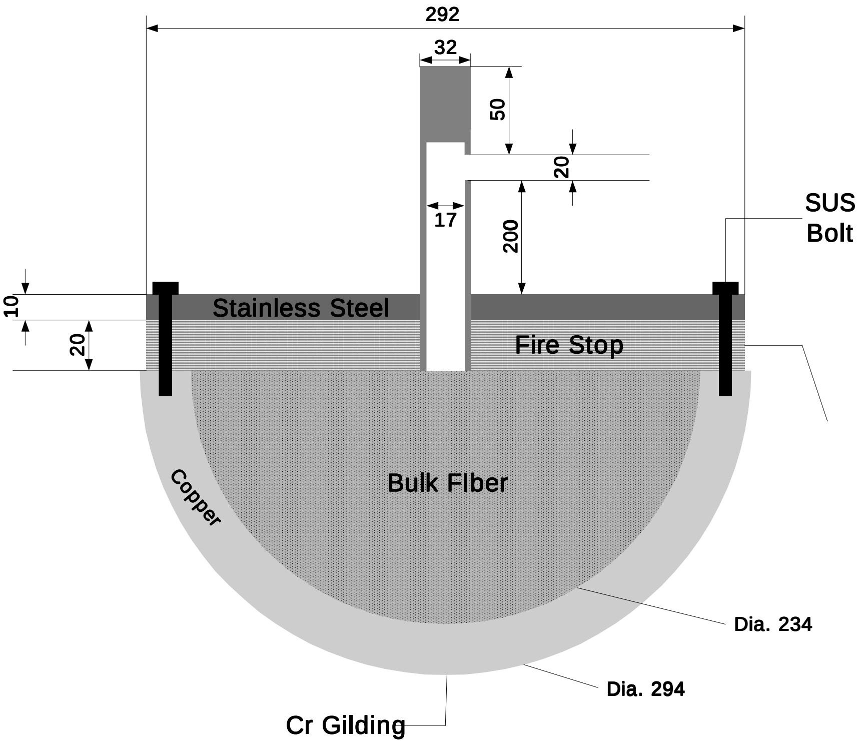

Figure 1. Cross-sectional View of Test Section

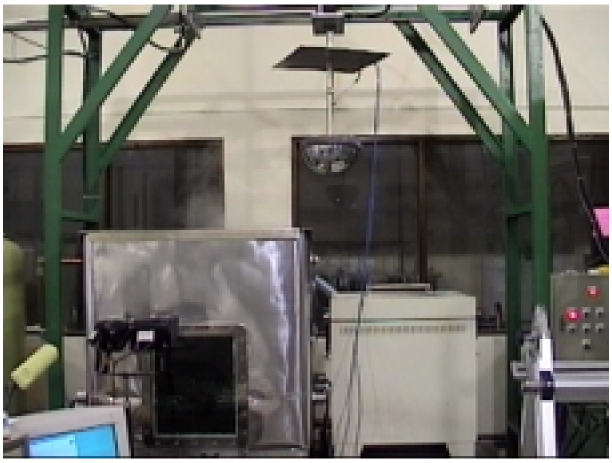

Figure 2. Picture of Experimental Facility DELTA

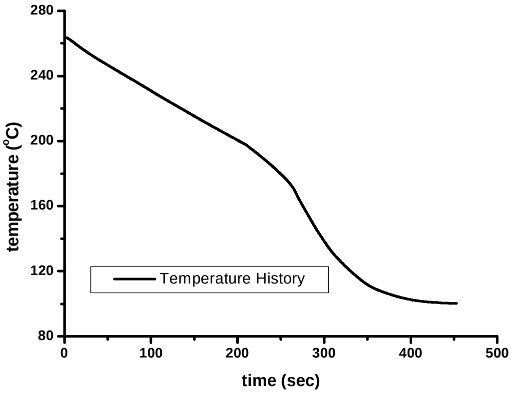

Figure 3. Temperature History in This Study

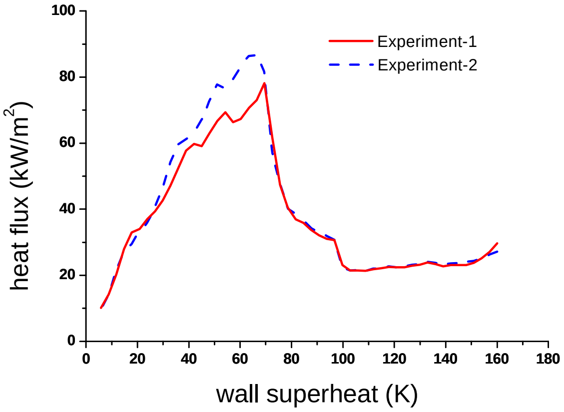

Figure 4. Boiling Curve

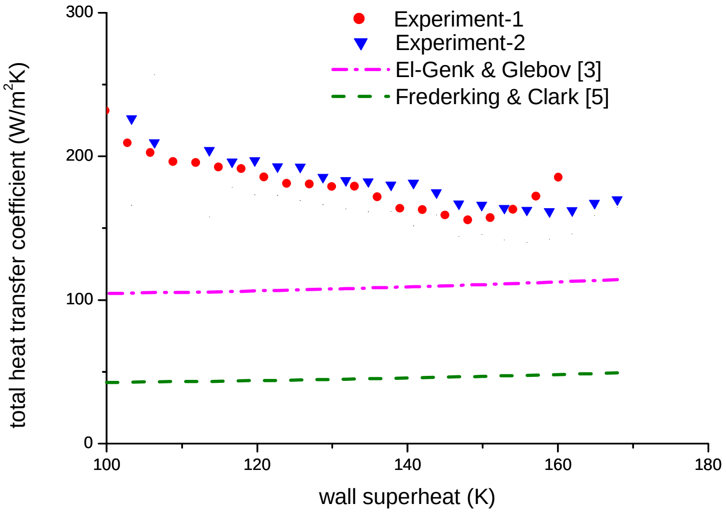

Figure 5. Film Boiling Heat Transfer Coefficient